Freeze-out of strange hadrons at RHIC

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Abstract. The production and freeze-out conditions of strange particles, produced in Au+Au collisions at RHIC energies, are studied within microscopic transport model. The system of final particles can be represented as a core, containing the particles which are still interacting with each other, and a halo, in which the particles have already decoupled from the system. In microscopic calculations hadrons are continuously emitted from the whole reaction volume. At RHIC, however, significant fractions of both mesons and baryons are emitted from the surface region within the first two fm/c. Different species decouple at different times. Strange mesons (kaons and ϕ) are frozen at earlier times and, therefore, can probe earlier stages of the reaction.

1. Space-time freeze-out picture

The main goal of the experiments with ultrarelativistic heavy-ion collisions at Brookhaven and CERN is to study properties of hot and dense hadronic matter. Using the measured final-state distributions one tries to reconstruct the dynamical picture of the nuclear reaction and compare it with the predictions of different models. The reaction dynamics and experimental constraints are so complicated at high energies that any single model cannot fully reproduce the whole set of data. But the discrepancies between the standard models and the data may help to reveal new phenomena associated with highly anticipated quark-hadron phase transition.

In the present paper we continue to study the freeze-out conditions in relativistic heavy ion collisions which were initiated earlier [1,2]. The calculations are carried out within the quark-gluon string model (QGSM) [3] for gold-gold collisions at $\sqrt{s} = 130$ AGeV. The phase-space distribution for the particles on the mass shell is a function of seven independent variables: components of radius $\vec{r}$ and momentum $\vec{p}$, and time t. For the sake of simplicity we integrate it over some variables and study separately different space-time and phase-space three-dimensional distributions. Note, that production and freeze-out of strange hadrons at RHIC energies have been studied also in [4] within the UrQMD model.

Figure 1 shows the distributions $d^2N/p_T dp_T dt$ and $d^2N/r_T dr_T dt$ of the emitted kaons and lambdas over time t and transverse radius and momentum, $r_T = \sqrt{(x^2 + y^2)}$ and $p_T = \sqrt{(p_x^2 + p_y^2)}$, respectively. It is different for Λ and K. One can see in Fig. 1 (right panels) that, in contrast to SPS [2], not only pions but also many kaons and lambdas are emitted from the surface region $r_T \approx R_A$ within first few fm/c. A strong collective transverse expansion of hadronic matter is observed. Kaons with large transverse momenta are emitted predominantly at the initial stages of the reaction (Fig. 1, left panels). They are produced in inelastic primary NN collisions,

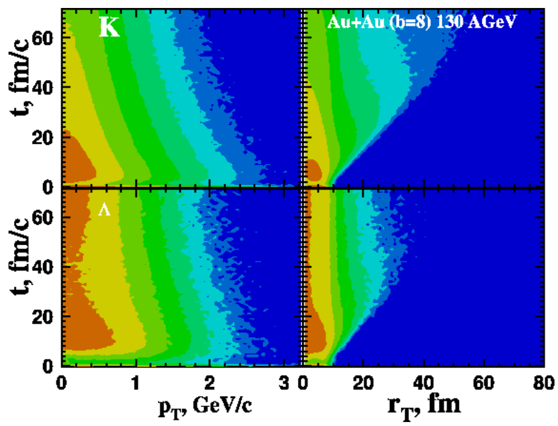

Figure 1. $d^2N/p_Tdp_Tdt/A$ and $d^2N/r_Tdr_Tdt/A$ distributions of the final-state K and Λ over their last elastic and inelastic collision points in the (p_T, t) and (r_T, t) planes. Particles are produced in Au+Au collisions with $b = 8$ fm at $\sqrt{s} = 130$ AGeV. Contour plots correspond to different particle densities.

whereas soft hadrons are emitted during the whole evolution time. At later times the transverse momenta are generated to a large extent by multiple rescattering. Both due to formation time effect and longer mean free path of kaons, similar distribution for lambdas is rather flat. This plateau corresponds to the "thermal" component of the Λ distribution due to many elastic and inelastic collisions. Still, the lambdas with maximum p_T are produced at the beginning of the collision. With growing time the transverse momentum spectra become gradually softer, which can be interpreted as the cooling of the expanding hadronic matter.

2. Sequential freeze-out

Let us consider in detail the time distributions for the different hadron species shown in Fig. 2. First of all, there is a noticeable difference between the meson and baryon groups of particles. The QGSM predicts that kaons and pions decouple earlier than nucleons and lambdas and approximately at the same times $\langle t^{\rm mes}\rangle \approx 6$ fm/c and $\langle t^{\rm bar}\rangle \approx 13$ fm/c. The width of dN/dt distributions for mesons are narrower than that for baryons: $\Delta t^{\rm mes} \approx 8$ fm/c and $\Delta t^{\rm bar} \approx 14$ fm/c. For the K's and Λ's the width is slightly smaller than the width for pions and nucleons, respectively. At the last stages of the reaction the dN/dt distributions for nucleons and pions are determined mainly by the resonance decays $\Delta \to \pi + N$, while the width of the distributions of kaons and lambdas is determined by the elastic collisions. At this stage K and Λ (as well as π and N) have the same decoupling times and the slopes of dN/dt distributions.

Therefore, the microscopic model calculations show that there is no sharp freeze-out of particles at RHIC. In fact, the particles are emitted continuously. In contrast to assumptions of ideal hydrodynamic model [5], the expanding fireball in microscopic models can be rather treated as a core consisting of still interacting hadrons, and a halo, which contains particles already decoupled from the system. The order of the

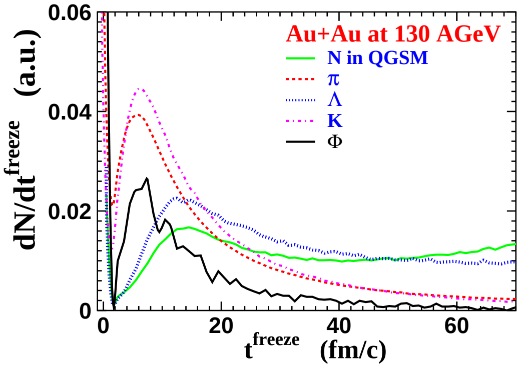

Figure 2. dN/dt distribution of N, π, K, Λ and ϕ over their last collision time t^{freeze}.

freeze-out of different species seems to be the same for energies ranging from AGS to RHIC: 1 - pions, 2 - kaons, 3 - lambdas, 4 - nucleons. This conclusion is valid also for the particles emitted in a certain rapidity interval, particularly at central rapidities, $|y| \leq 1$. On the other hand, the bulk production of mesons takes place within 8-10 fm/c, and the scenario of at least sequential freeze-out of hadrons is not ruled out.

Results of our microscopic calculations justify the implementation of the continuous freeze-out of particles in a more realistic 3+1 dimensional hydrodynamic model in [6]. It appears, for instance, that this approach can be accounted for better description of experimental data on the two-particle interferometry at RHIC.

3. Freeze-out and elliptic flow

The continuous freeze-out of particles modifies distributions connected to asymmetry of the system. One of this signals which is intensively studied now is elliptic flow, v_2 [7]. Figures 3 and 4 depict anisotropy of distributions for kaons and lambdas in the transverse coordinate (x, y) and momentum (p_x, p_y) planes at the beginning and at the end of the collision, respectively. At the initial stage of the reaction the distributions of particles possess strong anisotropy in the coordinate space, but quite weak anisotropy in the momentum one. Then the momentum-space anisotropy starts to develop for low-momentum particles, and at the final stage both kaons and lambdas show quite noticeable momentum anisotropy, i.e. elliptic flow. It is worth mentioning that the final distribution $d^2N/dxdy$ for Λ has wide plateau located between the centers of colliding nuclei. For kaons this distribution is much narrower; like pions, kaons are mostly concentrated within the overlapping region. Our analysis shows [8] that the baryonic and mesonic components of the elliptic flow are completely different: pions and kaons emitted from the surface of the expanding fireball within the first few fm/c carry the strongest flow, while later on their flow is significantly reduced. In contrast to this, the baryon fraction acquires stronger elliptic flow during the subsequent rescatterings, thus developing the hydro-like flow. The saturation of the flow at the

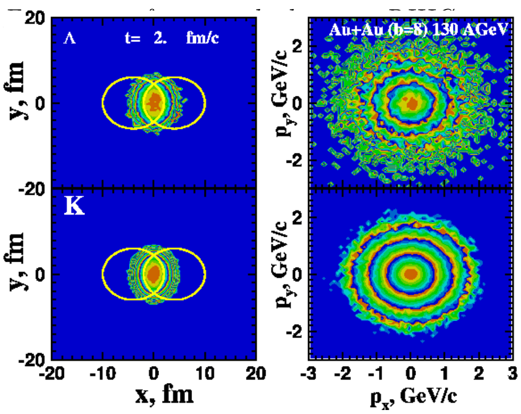

Figure 3. $d^2N/dxdy$ distributions for Λ and K in Au+Au collisions with $b = 8$ fm at $\sqrt{s} = 130$ AGeV.

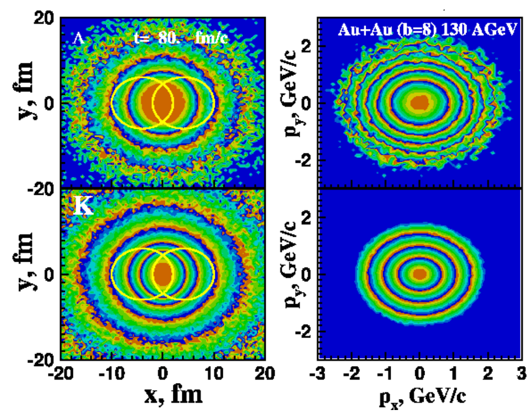

Figure 4. d^2N/dp_xdp_y distributions for Λ and K in Au+Au collisions with $b = 8$ fm at $\sqrt{s} = 130$ AGeV.

late stages can be explained by the lack of rescattering, since the expanding system becomes more dilute. Further details of the evolution of v_2 are considered in Ref. [9].

4. Conclusions

Our main conclusion is that the quark gluon string model predicts a continuous emission of particles, starting almost from the beginning of the reaction. This can be attributed to the lack of attractive forces which keep the particles together. To get a sharp freeze-out it is necessary to have some glue mechanism, like attractive mean fields, enhanced cross sections or rapidly hadronizing quark-gluon plasma. Different species decouple at different times. The order of the freeze-out of hadronic species is as follows: 1 - pions; 2 - kaons; 3 - lambdas; 4 - nucleons. At RHIC energies significant fractions of mesons and baryons are emitted within the first two fm/c. The mesons with large transverse momenta p_t are predominantly produced at the early stages of the reaction. The low p_t component is populated by mesons coming mainly from the decay of resonances. This explains naturally the decreasing source sizes with increasing p_t, observed in Hanbury-Brown−Twiss interferometry.

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